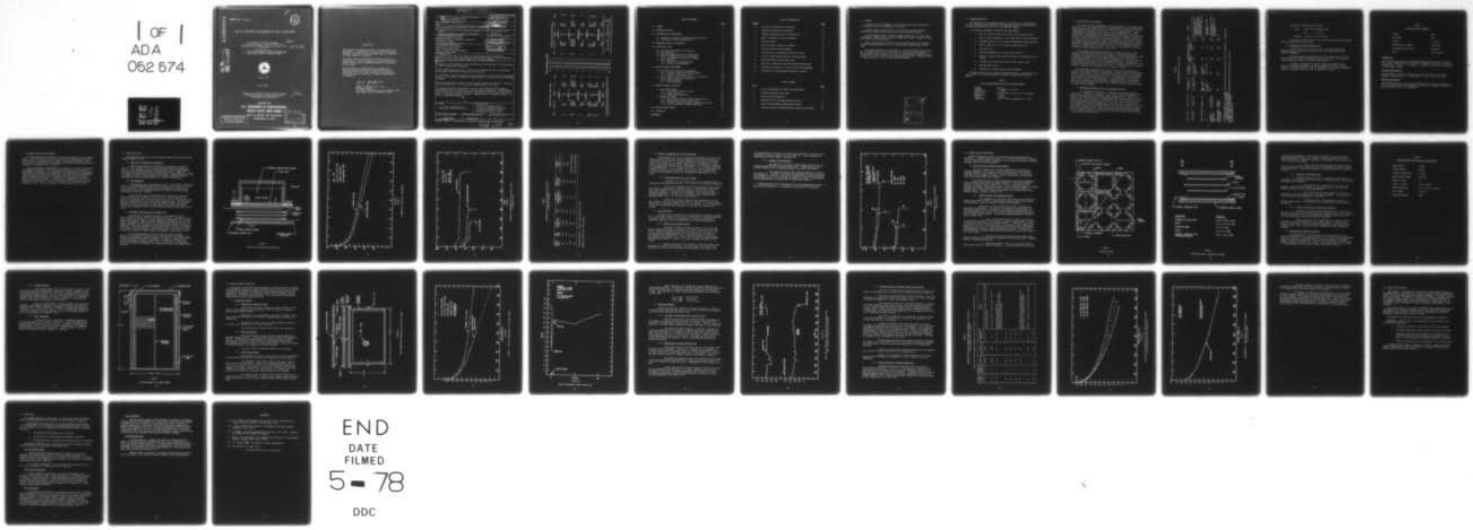
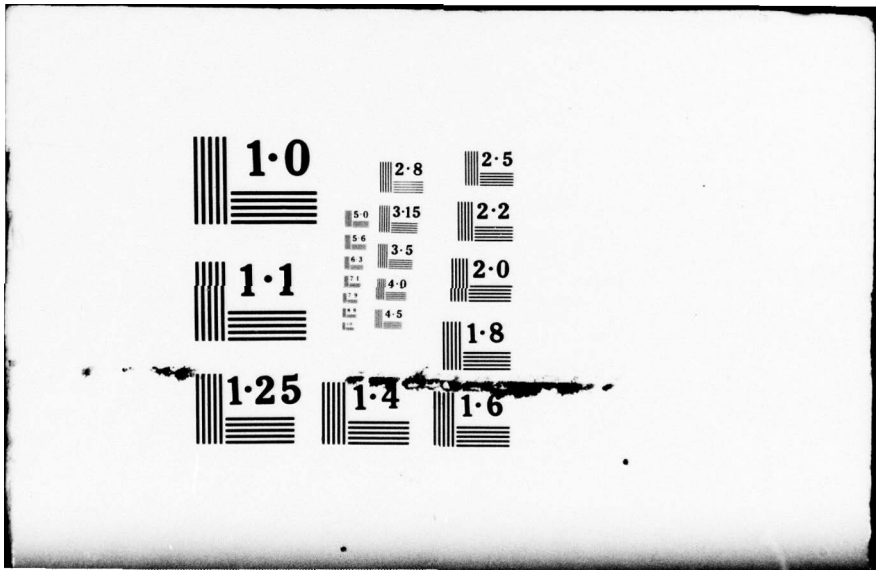
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430 Mountain Avenue, Murray Hill, New Jersey 07974

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Under contract to:
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16. Abstract

A program for the development of air-breathing fuel cell batteries for the operation of aids to navigation is discussed.

Calcium hydride is used as fuel. The fuel cell batteries provide a significantly higher energy density than conventional power sources.

The development focuses on battery system suitable for U.S. Coast Guard requirements. Modules with a capacity of 6KWH and a nominal rating of 2 watts at 13 volts are being developed.

Design and evaluation of single cells and battery modules are discussed. Testing is performed mostly with a U.S. Coast Guard flasher using a 1.15A lamp.

The program discussed in this report is a first step towards the development of hydride-based fuel cell batteries for use with aids to navigation. The development effort carried out so far has confirmed the suitability of the hydride cell for the design of high energy density batteries. Additional work is required, however, to arrive at applicable hardware.

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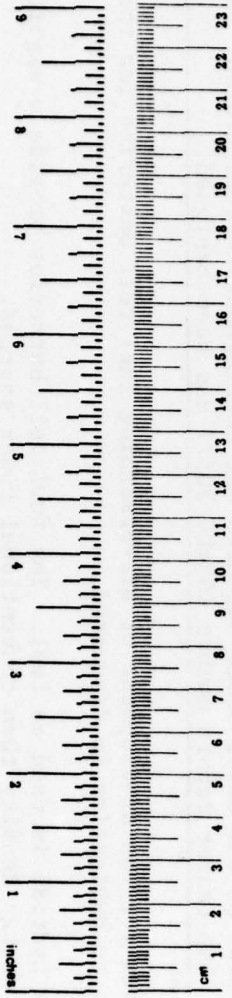
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

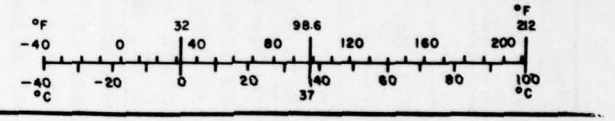


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1.0 SUMMARY

A program for the development of air-breathing fuel cell batteries for the operation of aids to navigation is discussed.

Calcium hydride is used as fuel. The fuel cell batteries provide a significantly higher energy density than conventional power sources.

The development focuses on battery system suitable for U.S. Coast Guard requirements. Modules with a capacity of 6KWH and a nominal rating of 2 watts at 13 volts are being developed.

Design and evaluation of single cells and battery modules are discussed. Testing is performed mostly with a U.S. Coast Guard flasher using a 1.15A lamp.

The program discussed in this report is a first step towards the development of hydride-based fuel cell batteries for use with aids to navigation. The development effort carried out so far has confirmed the suitability of the hydride cell for the design of high energy density batteries. Additional work is required, however, to arrive at applicable hardware.

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2.0 PROGRAM OBJECTIVES

The objective of the program discussed in this report is the development of fuel cell-based power sources for the operation of aids to navigation such as buoys, shore-based A/N, fog horns, and railroad signals.

The following performance characteristics are desired:

1. Use of a readily available fuel which can be handled safely
2. Cost of power comparable or lower than that of primary batteries
3. Reliability equal to or exceeding conventional primary batteries
4. Mission length of up to six years in prime power use
5. Long shelf life
6. Operating temperature of at least 28°F to 110°F
7. Ability to operate under pulsed load with no intermediate power storage
8. Possibility for remote monitoring of fuel supply status
9. Operable under motion
10. Suitable for refueling without heavy equipment

The above listed items are general program objectives. The specific goal of the effort is to develop batteries suitable for the mission listed in Table 1.

TABLE 1

MISSION REQUIREMENTS FOR FUEL CELL POWER SOURCE

Voltage	$\geq$13.0 V
Capacity	37.4 KWH at 13.0 Volts
Average Load	1.7 Watts
Duty Cycle	3.6 sec. off, 0.4 sec. on, 10 hours/day
Maximum Load	17 Watts
Mission	6 Years
Temperature	28°F - 110°F, if possible 0°F - 110°F

3.0 INTRODUCTION AND BACKGROUND

Fuel cells have been considered for the development of low wattage power sources (1) with the assumption that in comparison to batteries, significantly higher energy densities and a lower cost of power may be attainable. Other considerations are improved shelf life or ease of rechargability. These expectations are justified by the inherent characteristics of fuel cells, nevertheless, low wattage devices developed so far have lacked the operational simplicity of batteries and also are not competitive in terms of reliability and cost. This is partly due to the greater complexity of fuel cells, which is caused by the need for product water removal and reactant supply regulation. This problem can be minimized, however, and several promising cell types are available. Examples are the methanol-air cell (2) with alkaline electrolyte and the acid hydrogen-air cell (3). The latter is comparatively attractive provided a suitable hydrogen source can be found.

In some applications gaseous hydrogen is a possible choice. It may become increasingly attractive as new methods for hydrogren storage are developed, for instance as interstitial hydride on iron-titanium alloys. This increases the storage density over compressed gas and is a safer mode of containing hydrogen (4). An alternative to hydrogen gas is certain metals and metal hydrides which can be used for hydrogen generation. The choice is limited primarily to metallic zinc and selected base metal hydrides which form hydrogen by reaction with water or water vapor. Comparative data for hydrogen sources of interest for low wattage devices appear in Table 2.

The development discussed in this report relies on metal hydrides as hydrogen source, specifically calcium hydride. Hydrides provide a high energy density and are highly reactive towards water and water vapor. This permits the use of product water from the fuel cell for hydrogen generation and also makes possible a cell design which requires no moving parts. The phosphoric acid cell was chosen for the development. Its application for low wattage devices was stimulated by work performed at MERDC Fort Belvoir and later at EMC under Contract DAAK02-72-C-0474. This contractual effort largely provides the basis for this program.

3.1 Operating Principles of Calcium Hydride Fuel Cell

The phosphoric acid matrix cell combined with calcium hydride as fuel source is potentially comparable in handling and operating simplicity to batteries yet promises a considerably higher energy density. Operation is based on the high reactivity of calcium hydride towards water vapor, a reaction which results in the formation of hydrogen and lime. This reactivity can be used for the removal of product water from the fuel cell by vapor diffusion. The hydride fuel is made an integral part of the fuel cell and located in close proximity to the electrode and exposed to its entire surface to facilitate water vapor transfer. The driving force is the water vapor gradient between the cell and the hydride bed. Under steady-state conditions the sustainable current density is directly proportional to the rate of water vapor diffusion to the unreacted hydride fuel.

TABLE 2

HYDROGEN SOURCES FOR FUEL CELLS

Hydrogen Source	DOT Classification	Hydrogen Generating Reaction	End Product to be Disposed of	Energy Density Based[1] on Reactants Excl. of H_2O WHrs/lb.	WHrs/inch^3	Cost/KWH $	Remarks
Calcium hydride	Flammable solid	$CaH_2 + 2H_2O_V \rightarrow Ca(OH)_2 + 2H_2$	Lime in form of fine powder or cake	865	50.7	6.10 (4)	Energy density in practical devices should approximate 1/3 to 3/4 of values in columns 5 and 6 on weight basis and 1/10 to 1/2 on volume basis
Sodium borohydride	Flammable solid	$NaBH_4 + 3H_2O_L \rightarrow NaBO_2 + 4H_2$	Sodium borate solution	1925	71.2	7.20 (4)	
Zinc		$Zn + 2NaOH \rightarrow Na_2ZnO_2 + H_2$	Zincate solution	125	13.4		Energy density based on metal only.
Hydrogen gas stored on iron titanium alloy	Classification not established	None	None	87 (2)	13.7 (2)	0.15 (3)	Energy density in practical devices should approximate values given in column 5.
Hydrogen compressed to 2200 psig in 1A cylinder	Flammable compressed	None	None	80 (2)	3.4 (2)	0.15 (3)	

---

(1) Based on reactants only. Fuel assumed to be 100% pure, current efficiency 100%, single cell voltage 0.75 V. Excludes weight and volume of fuel cell and container.
(2) Includes container weight and volume.
(3) Based on $6 per 1000 ft^3 hydrogen gas, excludes handling and storage which may be significant.
(4) 5000 lb. lots, Oct. 76. (Ventron)
(5) Assumes $0.50/lb. zinc.

The overall reactions are as follows:

Anode: $CaH_2 + 2H_2O \rightarrow Ca(OH)_2 + 2H_2$

$2H_2 \rightarrow 4H^+ + 4e$

Cathode: O_2 (Air) + $4e + 4H^+ \rightarrow {}_2H_2)$

The product water is formed on the air electrode and diffuses through the electrolyte to the hydride fuel.

3.2 Properties of Calcium Hydride Fuel

The fuel selection is one of the most critical considerations. Hydrides provide a high energy density but are also comparatively costly sources of hydrogen.

Calcium hydride was selected because of its lower cost relative to other hydrides, its handling characteristics and specifically its reactivity towards water vapor even at low ambient temperatures.

A further consideration is the fact that the reaction product - lime - is comparatively harmless and may be disposed of on-site. Calcium hydride is currently supplied in the United States only be Ventron Corporation. Pertinent information about the fuel is summarized in Table 3.

TABLE 3

CALCIUM HYDRIDE PROPERTIES

Formula	CaH_2
Mol Weight	42.10
Density	1.7 g/cm^3
Bulk Density (-4 Mesh)	0.85 g/cm^3
Bulk Density Used (Lime)	0.53 g/cm^3
Purity	93-97 Percent

Availability:

Calcium hydride is available in quantities varying from one pound to carload lots. Purity ranges from 93 to 96 percent depending on mesh size. Mesh sizes available are: -40 mesh, -4 + 40 mesh, -1 + 4 mesh, 1 inch lum to -4 mesh and 1 inch irregular lumps.

Packaging and Shipping:

Calcium hydride is shipped in friction top cans, metal pails, and drums. Shipment is governed by I.C.C. Regulations: 73:153, 75:154, and 73:206.

Handling and Storage:

Calcium hydride is safely and easily handled and stored and may be ground in air. As it decomposes in the presence of moist air, it should be handled with minimum exposure to air of high humidity.

4.0 PROGRAM EXECUTION AND REPORTING

The development effort discussed in this report consists of three separate tasks: first, a single-cell study in which basic cell performance is determined; second, the development and testing of an engineering battery model; and finally, the fabrication and testing of pre-prototype and prototype battery systems for the missions given in Table 1.

The work performed is summarized in two sections. The first is concerned with single-cell testing. Cell discharge characteristics and the effect of environmental conditions on cell performance are discussed and also questions relating to fuel utilization are addressed. The reporting of the engineering effort deviates from the original program plan but more clearly states the actual development undertaken. It describes the development of a battery module and its testing either as a single unit or combined into systems comprising up to three units. The latter represents the pre-prototype systems referred to above. Finally, a design for the prototype system is given.

5.0 SINGLE-CELL STUDY

Data reported in this section were developed under this program and under Contract DAAK02-72-C-0474.

5.1 Test Cell for Single-Cell Evaluation

Testing was performed in Plexiglass cells with an active area of 19.6 or 81 cm^2. Details of the test fixture used predominantly appear in Figure 1. The electrode and matrix are supported by 1.25 cm thick honeycomb or a 6 mm thick perforated board to assure uniform contact. Current is collected by a screen, metal strips or Grafoil sheet. The hydride fuel (crushed to -4 mesh) is placed in close proximity of the anode, separated from the electrode only by the electrode support and a sheet of filter paper.

5.2 Cell Components

Cell components have been developed prior to this program. Electrodes consist of Teflon-impregnated carbon paper activated on one surface with 2 to 4 mg Pt black/cm^2. Electrodes have not been optimized for the specific use and catalyst loadings are considered larger than required for this program, particularly on the fuel electrode.

The electrolyte matrix predominantly used consists of stabilized Teflon gel with a pore volume of 55 to 60 percent. The thickness of the matrix is 0.55 mm and that of the electrode 0.3 to 0.6 mm. "As prepared," the matrix is impregnated with 95 to 100 percent phosphoric acid. For some experiments the acid content of the matrix was increased by soaking in 95 percent phosphoric acid for three hours. In addition to this matrix, glass-fiber filter paper impregnated with 50 percent phosphoric acid was also used in some tests.

5.3 Discharge Characteristics of Single Cells

The hydride cell performs essentially as a hydrogen-air cell. Voltage levels are lower, however, under many conditions. The hydride cell is "fuel limited" and voltages are reduced compared to hydrogen by the low partial pressure of hydrogen. Single cells were discharged over periods of up to one month. Frequently the same cells were used for repeated testing with new fuel charges and total hours accumulated on individual cells were well in excess of 1000 hours. Cells used repeatedly showed some decline in open circuit voltage and increase in cell resistance. This was later found to be due to the loss of electrolyte because of neutralization with ammonia. (See Section 7.2.4.)

Cells were discharged at constant load and constant voltage. Initial cell performance with hydrogen and hydride is shown in Figure 2, and discharge characteristics appear in Figure 3 and Table 4. Under constant load cell voltage declines initially considerably. Subsequently, however, the voltage stabilizes and remains constant until the cell is fully discharged. The initial decline is attributed to a progressive decrease in hydrogen partial pressure.

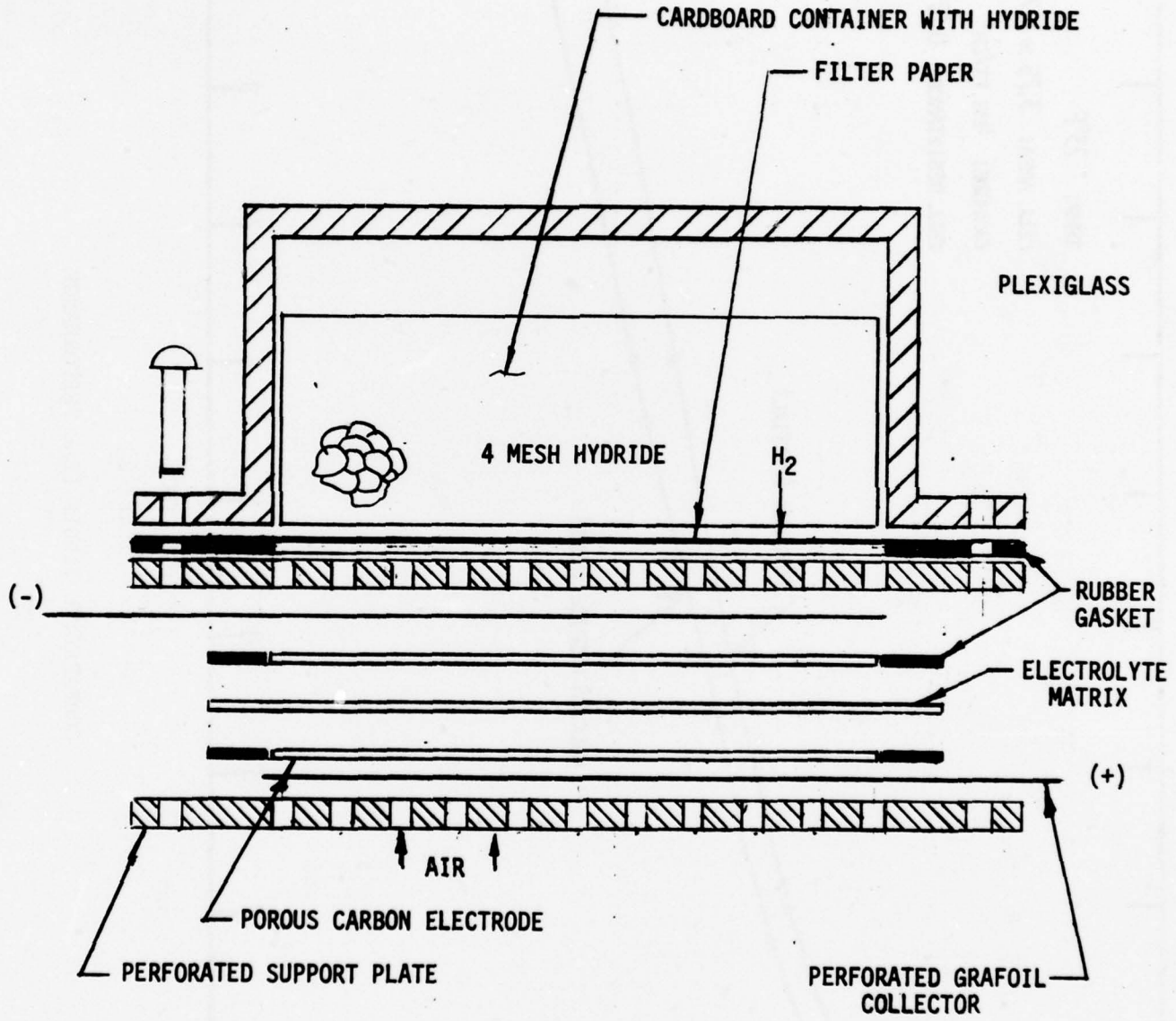


FIGURE 1

TEST CELL FOR SINGLE-CELL EVALUATION

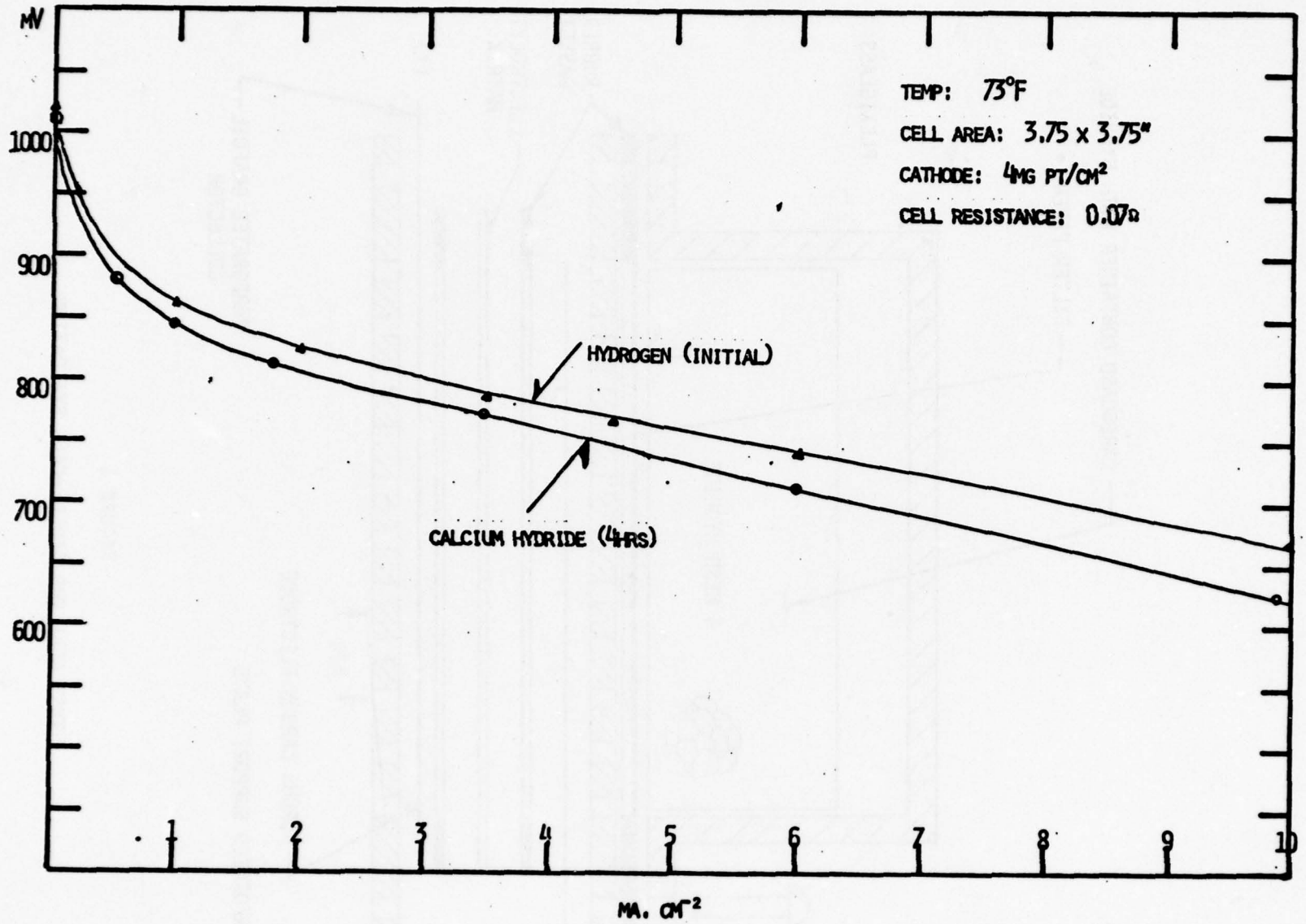


FIGURE 2

COMPARATIVE SINGLE-CELL PERFORMANCE

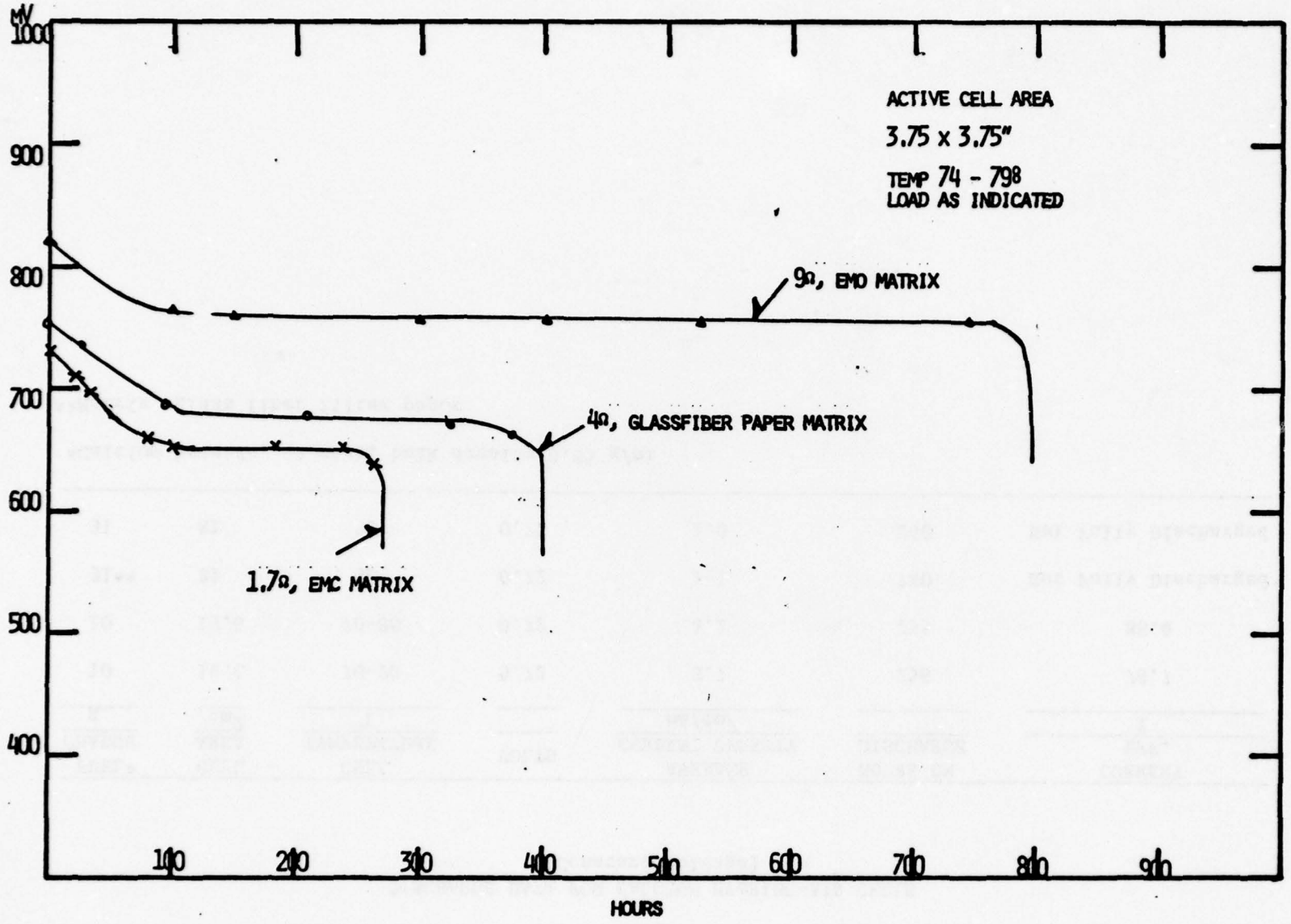


FIGURE 3

DISCHARGE CHARACTERISTICS OF HYDRIDE CELLS
(Constant Load)

TABLE 4

DISCHARGE DATA FOR CALCIUM HYDRIDE-AIR CELLS
(Constant Voltage)

FUEL* CHARGE g	CELL AREA cm^2	CELL TEMPERATURE °F	VOLTS	AVERAGE CURRENT DENSITY mA/cm^2	HOURS ON DISCHARGE	CURRENT EFF. %
10	19.6	70-80	0.72	3.7	256	78.7
10	19.6	70-80	0.72	4.2	255	88.6
31**	81	38	0.72	1.1	740	Not Fully Discharged
31	81	38	0.72	1.0	240	Not Fully Discharged

*Calcium hydride, -4 mesh, bulk density 0.85 g/ml

**Matrix, glass fiber filter paper

5.4 Effect of Temperature on Cell Performance

The phosphoric acid cell is operative with hydrogen fuel over a wide range of ambient conditions, including temperature well below freezing (5). If hydrides are used as fuel, however, performance is limited at low temperatures by the reduced rate of hydrogen generation as the diffusion of water vapor to the hydride fuel decreases. Nevertheless, cell operation is possible at low temperatures. At 3°C, current densities of 1.0 to 1.1 mA/cm^2 could be sustained (Table 4) at a cell voltage of 0.72 volts. Earlier measurements (6) of the rate of water vapor diffusion through hydride beds, indicate that practical current densities should be sustainable at temperatures as low as -12°C.

5.4.1 Performance Loss Upon Cell Cooling

A peculiarity of the hydride cell is the transitory loss in performance encountered upon cooling. It is caused by the following conditions:

For a given temperature the acid concentration in the electrolyte membrane equilibrates to a specific level. As the cell is cooled, the water vapor pressure of the electrolyte decreases and the ability of the electrolyte membrane to transfer water diminishes. Thus, little hydrogen is generated temporarily. This effect is illustrated by the following test performed with a cell of 81 cm^2 active area (Figure 1).

Loaded with 20 ohms, voltage at room temperature is 0.76V. Upon cooling to 3°C, the voltage drops within two hours to 0.74 volts and then output ceases as hydrogen present in the cell is consumed. At 3°C approximately 24 hours in a water-saturated atmosphere are required for performance to recover.

5.5 Fuel Utilization

The high cost of the hydride fuel necessitates its efficient utilization. Two possible reasons for fuel loss, the generation of excessive hydrogen by moisture taken up by the cell from ambient air and cross-diffusion of reactants, followed by direct recombination, are briefly discussed below.

5.5.1 Effect of Air Humidification

The amount of moisture possibly present in the air at high ambient temperature entails a significant fuel loss if taken up by the cell. Thus at 110°F and 100 percent R.H. about one-third of the fuel could be lost due to excessive hydrogen generation if air is supplied at two times the stoichiometrically required rate, and all moisture is taken up by the cell. The extent to which moisture is, in fact, taken up cannot be readily assessed and presumably depends on a number of factors, including the specific cell design.

Several experiments were performed to obtain an indication of possible fuel losses from this source. For this purpose, the amount of air admitted to the cell and its humidification was varied. Air access to the

cell was restricted by placing a 1/8 inch thick board with a 1/8-inch hole in the center over the air side of the cell (Figure 1). Fuel utilization is significantly affected (Figure 4 and Table 4).

5.5.2 Reactant Cross-Diffusion

The magnitude of reactant cross-diffusion could not be conclusively determined with operating hydride cells. Meaningful data were obtained, however, with an available phosphoric acid fuel cell stack.*

Cell components used in this stack are identical to those in the hydride cell. Reactant cross-leakage was determined by purging the stack with hydrogen or a mixture of nitrogen (90 percent) and hydrogen (10 percent) and measuring the gas volume entering and leaving the stack. Cross-diffusion rates corresponding to 0.6 mA/cm^2 and 0.1 mA/cm^2 were observed.

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*This stack is part of a hydrogen-air cell sold commercially by EMC (Model 15) and consists of 12 cells with an active area of 25 cm^2 each.

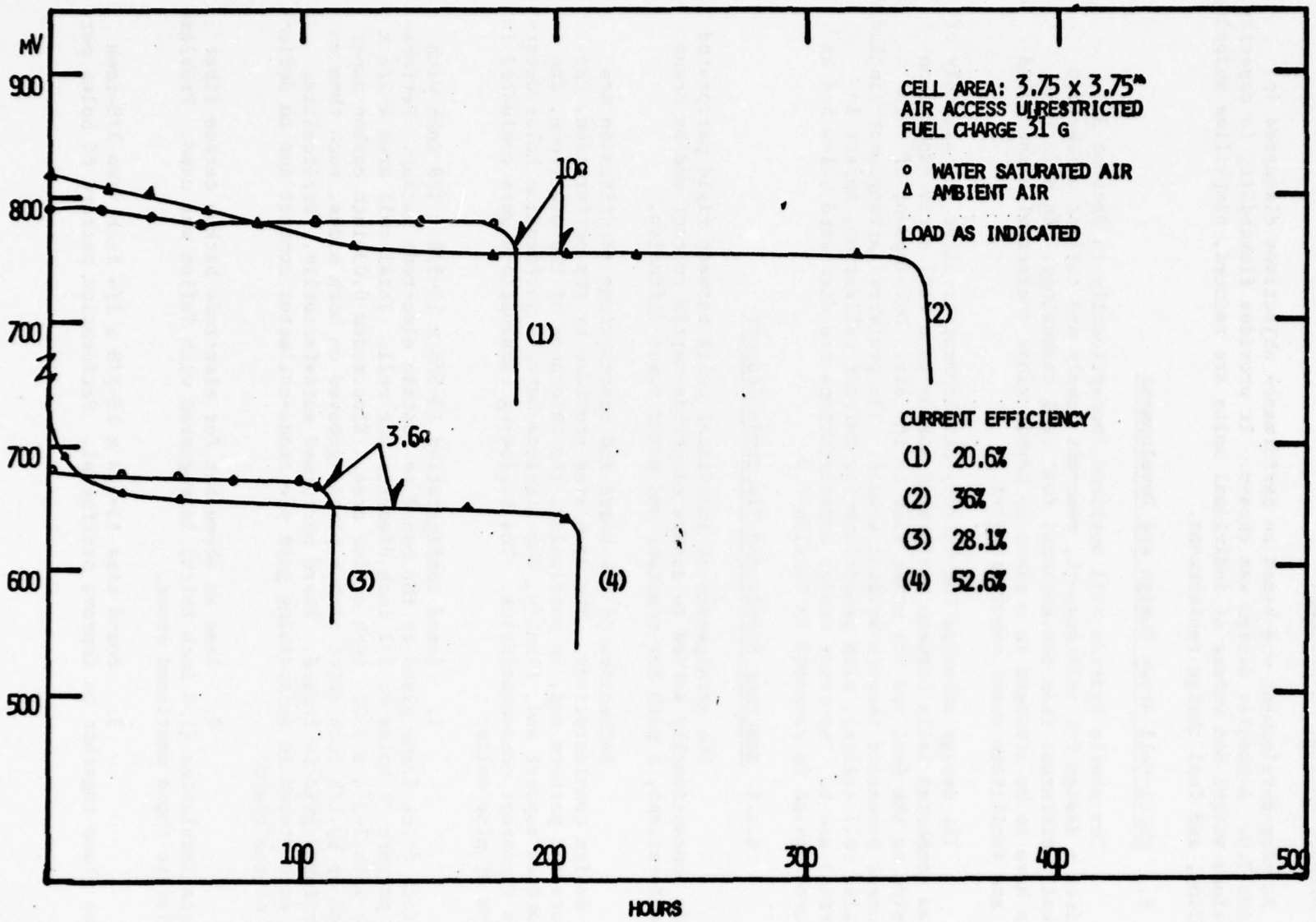


FIGURE 4

EFFECT OF HUMIDITY ON CELL PERFORMANCE
(Constant Load)

6.0 HYDRIDE BATTERY DEVELOPMENT

Battery development was based on performance objectives discussed in Section 2.0. A modular design was chosen. It provides flexibility in capacity and since weight and volume of individual units are reduced, simplifies shipping, handling, and fuel charge replacement.

6.1 Multi-Cell Array Design and Development

The static hydride cell outlined conceptionally in Section 3.1 requires a design for cell support, reactant supply and current collection radically different from conventional fuel cell technology. In principle, cells have to be arranged in a plane to permit close contact with the solid fuel and facilitate water vapor transfer.

The design selected for battery development involves the assembly of series connected cells between perforated boards to a cell array exposed on one side to the fuel and the other side to the air. Development of this component proceeded through several stages. The preferred arrangement (including detailed cell design), with provisions for current collection, appear in Figures 5 and 6. Important design considerations are discussed below and an improved design is proposed in Section 8.0.

6.1.1 Reactant Supply and Electrode Support

The arrangement of individual cells between rigid perforated boards conceptionally serves to assure electrode-matrix contact and by means of perforations, a path for reactant and water vapor diffusion.

Deflection of the board and restrictions to diffusion are main design considerations. The open area provided by the perforation, the perforation pattern and, in particular, the thickness of the electrode, its perforated support and, finally, the distance between perforation holes determines transport characteristics. The following combinations were evaluated in arrays of nine cells:

1. Board configuration 13-5/8 x 13-5/8 x 1/8 inch with 1/8 inch thick frame glued to the board to contain electrode backup. Perforation pattern 25 holes of 1/2 inch diameter per cell. Total cell area 4-1/8 x 4-1/8 with 3-3/4 x 3-3/4 inch active area. Electrodes 0.03-inch carbon paper backed up by 1/8 inch thick carbon plates grooved on both sides, such than an interlinked grid is formed. Board performed satisfactorily. Difficulties were encountered in maintaining good electrode-collector contact due to deflection of the board.

2. Same as above but for electrode backup carbon fiber furnace insulation (1/8 inch thick) impregnated with Teflon was used. Problems similar to those mentioned above.

3. Board size 13-5/8 x 13-5/8 x 1/4 inch (two 1/8-inch plates glued together to improve stiffness). Perforation pattern 64 holes per

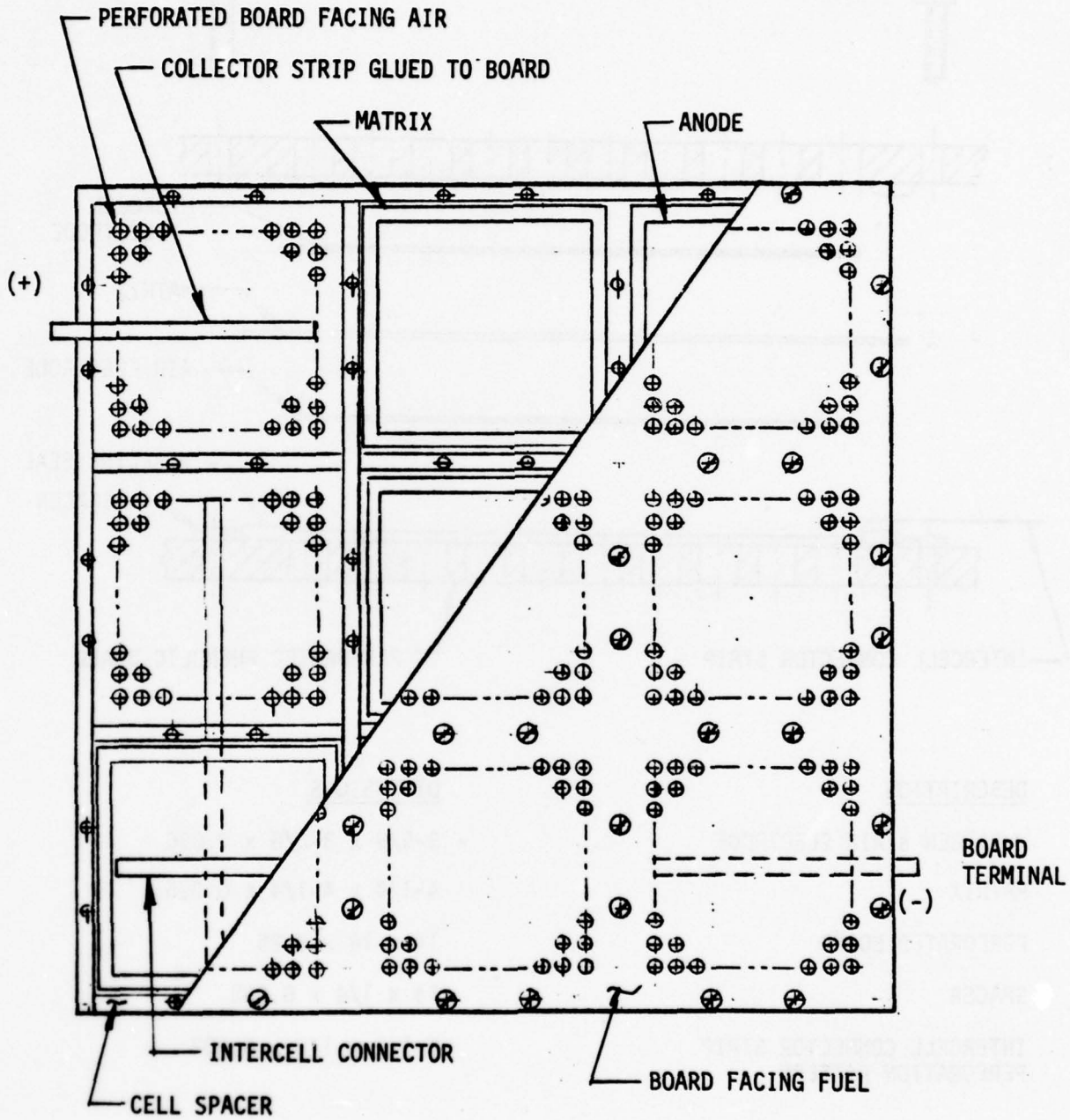
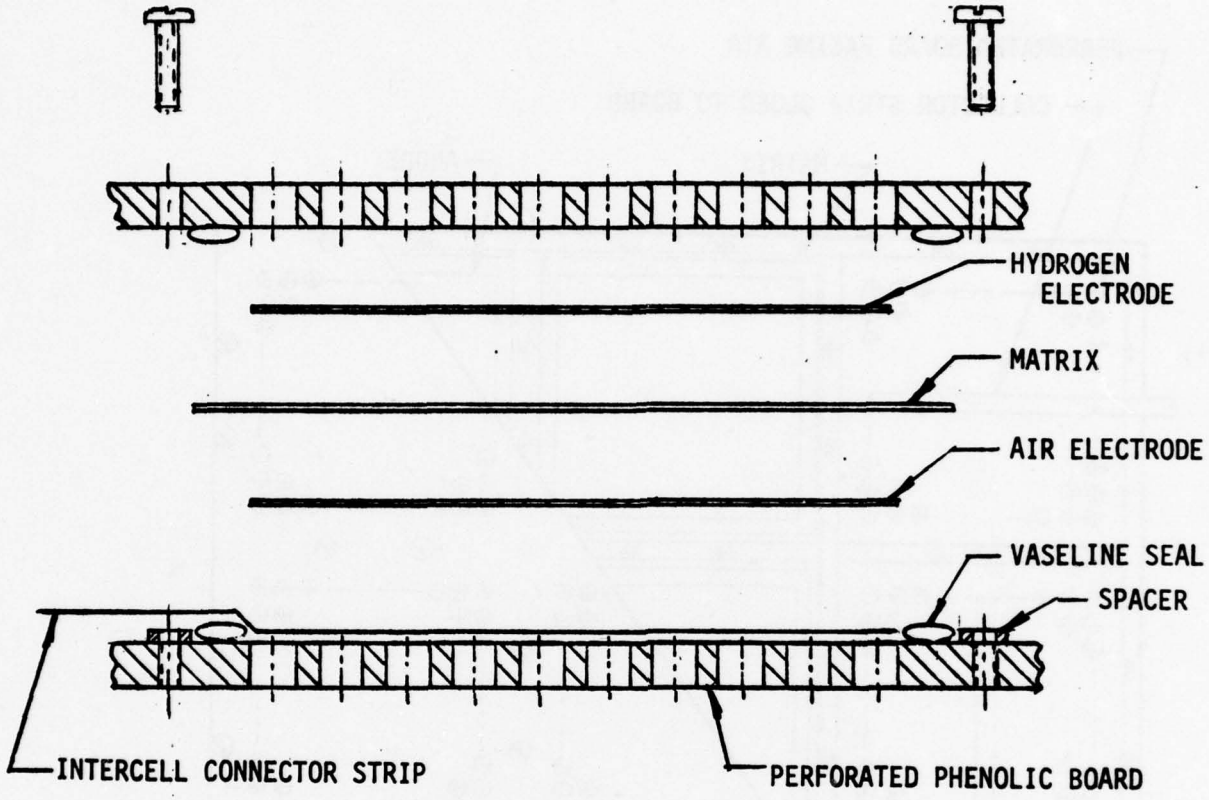


FIGURE 5

NINE-CELL ARRAY



DESCRIPTION	DIMENSIONS
HYDROGEN & AIR ELECTRODE	3-5/8 x 3-5/8 x 0.030
MATRIX	4-1/4 x 4-1/4 x 0.025
PERFORATED BOARD	14 x 14 x 0.25
SPACER	14 x 1/4 x 0.065
INTERCELL CONNECTOR STRIP PERFORATION PATTERN	8-1/2 x 1/8 x 0.002

FIGURE 6

NINE-CELL ARRAY, SINGLE-CELL ASSEMBLY

cell of 3/8 inch diameter. Total cell area and active area same as above. Electrode backup only used on the cathode. Consists of sheet of 0.03 inch thick carbon paper. Performance satisfactory, but weight increased due to the use of 1/4 inch thick board.

4. Same as 3 but for added stiffness 1/4-inch honeycomb with 0.06-inch perforated cover sheet used for fabrication of boards. Performance satisfactory. This approach appears to be most suitable if a large cell is used.

6.1.2 Sealing of Individual Cells

Leakage along the cell edge is potentially a main source of fuel loss. The electrolyte matrix was used as a sealing surface. The following arrangements were examined:

1. EPR gasket on one or both sides of the electrolyte membrane. Seal was unsatisfactory because of deflection of the board and gradual deformation of the electrolyte membrane.

2. EPR closed-cell foam rubber gasket on both sides of the matrix to increase tolerance to dimensional variations. Seal was unsatisfactory because of gas permeability of the foam.

3. A satisfactory seal was obtained with layers of Vaseline placed alone or in combination with a rubber gasket on both sides of the matrix.

6.1.3 Current Collection and Inter-Cell Connection

Current is collected from the electrodes by a 1/8 inch wide and 0.02 to 0.05 inch thick metal strip placed along the center of the electrode. Series connection of cells is accomplished by extending the metal strip over two cells connecting a positive and negative electrode.

Current collection with a metal strip was chosen over edge collection with Grafoil sheets for the following reason: conduction path within the electrode is shorter and contact resistance between electrode and collector lower. Also, the Grafoil sheet interferes with cell sealing and assembly.

6.2 Battery Module Design Development

The battery module is conceived as a self-contained unit with a power rating sufficient to satisfy the majority of U.S. Coast Guard requirements. Capacity is limited to permit handling in the fully charged and discharged condition without heavy equipment. Based on the design chosen, a total of six modules connected in parallel are required to meet the mission listed in Table 1. Design parameters of the battery module are listed in Table 5.

TABLE 5

NOMINAL BATTERY MODULE DESIGN SPECIFICATIONS

Power Rating	2 Watts
Current Rating	155 mA
Voltage at Rated Load	13 Volts
Open Circuit Voltage	18 Volts
Number of Cells	18
Active Cell Area	3-5/8 x 3-5/8"
Module Dimensions	9-3/4 x 14-3/4 x 15-1/2"
Fuel Charge	11-1/2 lb.
Projected Capacity	6 kwh

6.2.1 Module Container

A fiberglass housing with a cover attached by latches is used as a module container. Arrangement of components is shown in Figure 6. Two series-connected cell arrays of nine cells each are mounted inside the fiberglass housing on opposing walls. The cell arrays are spaced 1/4 inch from the container wall forming a gap which serves as air manifold. Air is admitted through a hole in the container wall. Module terminals are located on one side of the container not covered by the cell array.

Prior to the fabrication of battery modules with a fiberglass container, a polyethylene container (1/4-inch wall thickness) was used for experimentation. Overall dimensions are somewhat different from those shown in Figure 7 (15-1/4 inch x 8-1/2 inch x 15 inch). A flange with a gasket and a flat cover is used to seal the container. Air is also admitted through a hole in the container wall (diameter 1 inch).

6.2.2 Fuel Containment

The hydride fuel is contained in a corrugated cardboard box of sufficient size to face the entire cell array. A paper honeycomb insert assures distribution and location of the fuel. Two boxes are considered per battery module. They are only partly filled to provide space for expansion upon conversion of the hydride to hydroxide. Design is based on a filling density of 0.3 g/ml using fuel crushed to -4 mesh size.

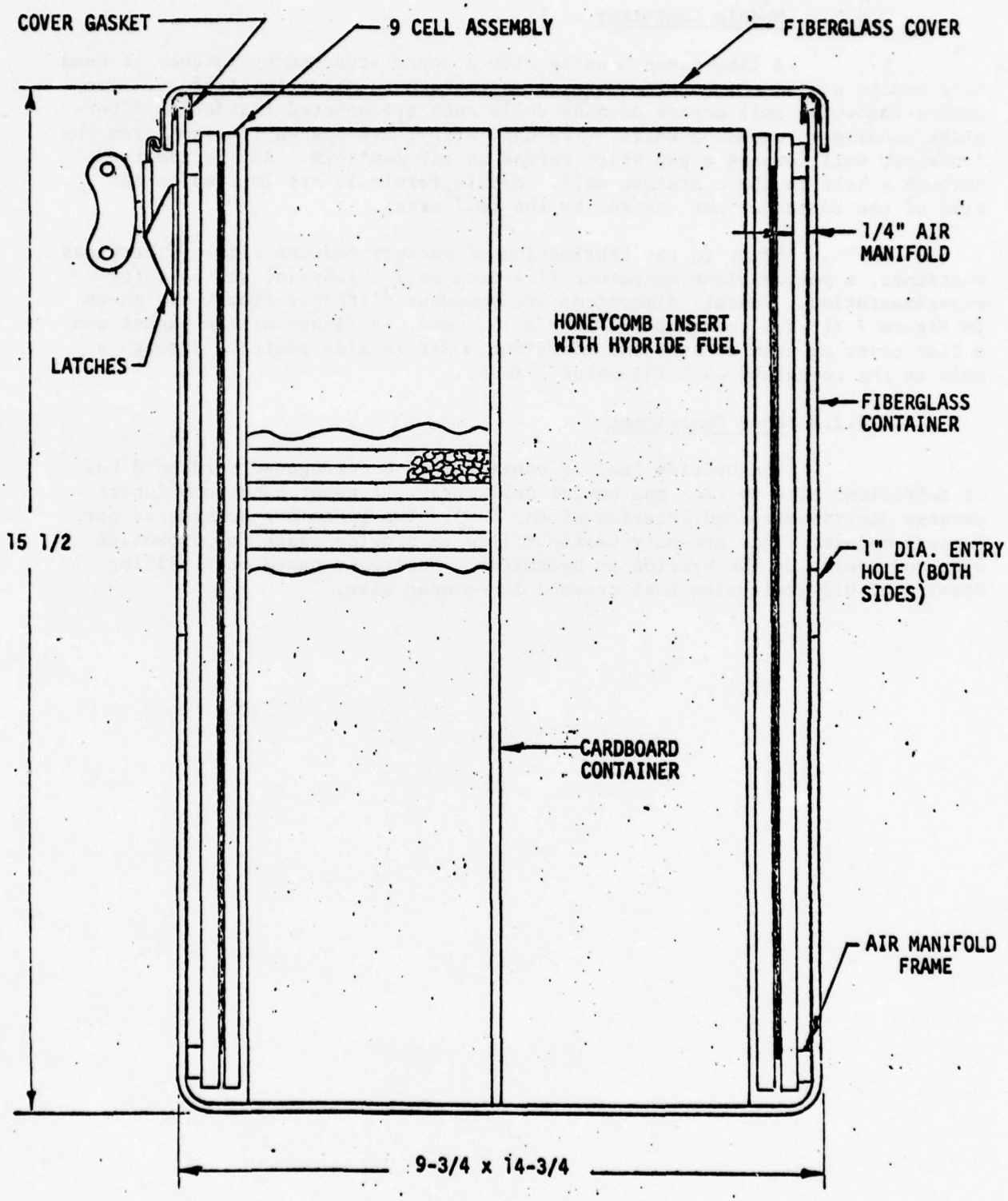


FIGURE 7

OUTLINE DRAWING OF BATTERY MODULE

7.0 HYDRIDE BATTERY EVALUATION

This section covers short-term and endurance testing of multi-cell arrays, battery modules, and module systems consisting of up to three units. Electrical performance with hydrogen and hydride fuel was determined under constant and pulsed load. Soundness of the design in terms of fuel containment, reactant distribution, and sealing was ascertained. Fuel utilization and degradation behavior were studied in three life tests.

7.1 Short-Term Testing

7.1.1 Evaluation of Nine-Cell Array

Cell arrays were tested routinely for short periods of time prior to their assembly in battery modules or for the purpose of failure analysis after module testing.

Uniformity of cell performance, tightness of assembly, resistance losses were determined with hydrogen, hydrogen-nitrogen, and calcium-hydride fuel.

Testing also provide inputs for design changes in respect to air supply, air distribution, or current collection.

The fixture shown in Figure 8 was used for the evaluation.

7.1.2 Module Evaluation

Initial performance of battery modules was determined with hydrogen-nitrogen mixtures. A representative current-voltage curve appears in Figure 9. Performance is consistent with the design goal given in Table 5. For operation with hydride fuel, modules were first purged with hydrogen. Approximately one hour is required to reach optimum output. This is attributed to the slow release of air trapped in the fuel container.

A practical start-up procedure remains to be developed.

7.1.3 Pulsed-Load Testing

The performance of hydride cells under pulsed load was examined on individual battery modules or systems consisting of up to three modules.

A CG-181 Model S 1069 flasher (input 10-18 volts, output 12 VDC) was used in the evaluation. Figure 10 illustrates performance with a 0.55 A lamp. Initially, for a period of 30 to 60 milliseconds, voltage drops severely. This drop is followed by a recovery peak, a slow decrease during flashing and a gradual increase after completion of the flashing cycle. The initial drop is caused by the current surge through the cold filament.

The voltage decline during the flash appears attributable to reactant depletion in the electrodes. Voltage during flashing seems noticeably higher than the cell voltage at the equivalent current density under constant load.

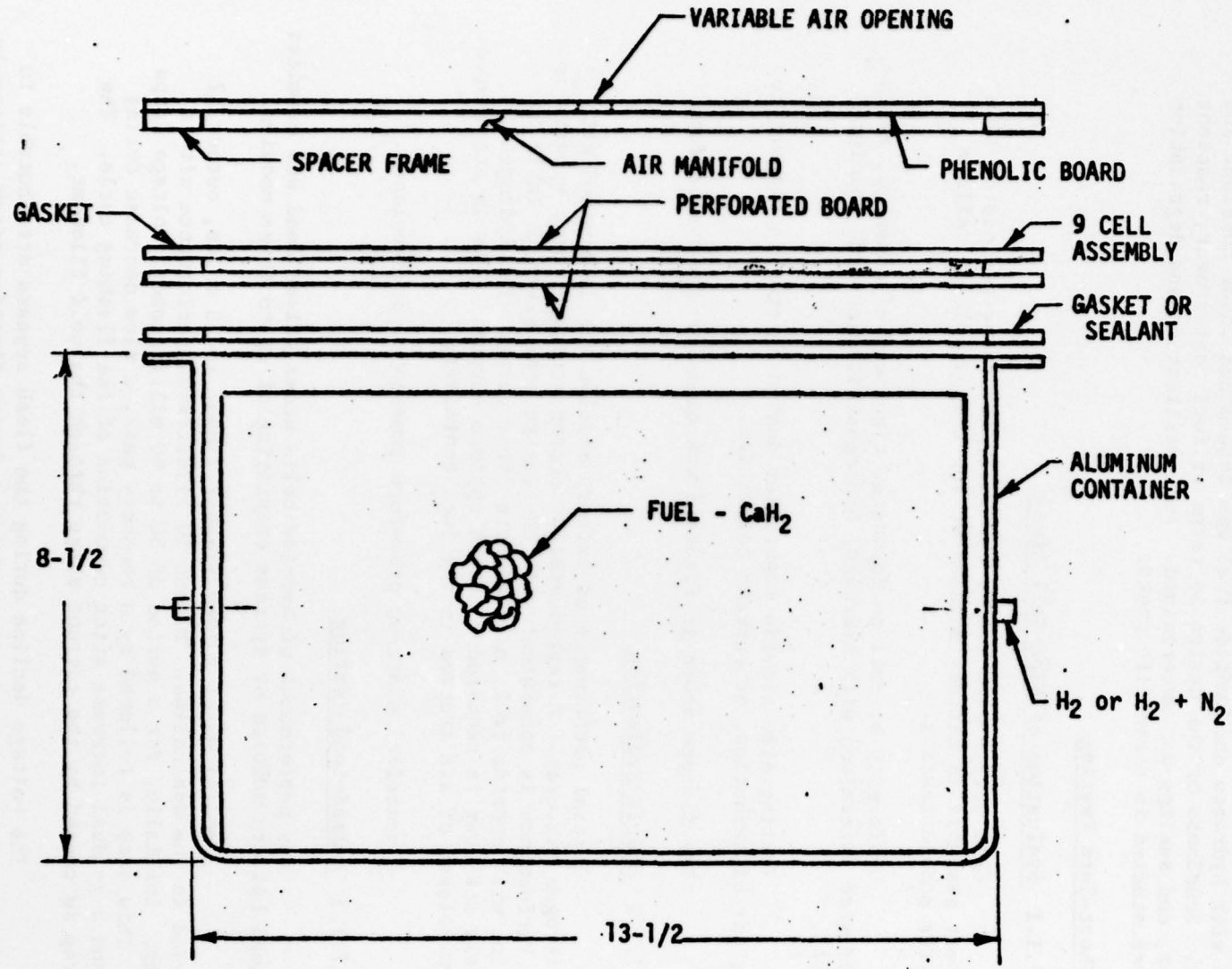


FIGURE 8

TEST FIXTURE FOR EVALUATION OF MULTI-CELL ARRAY

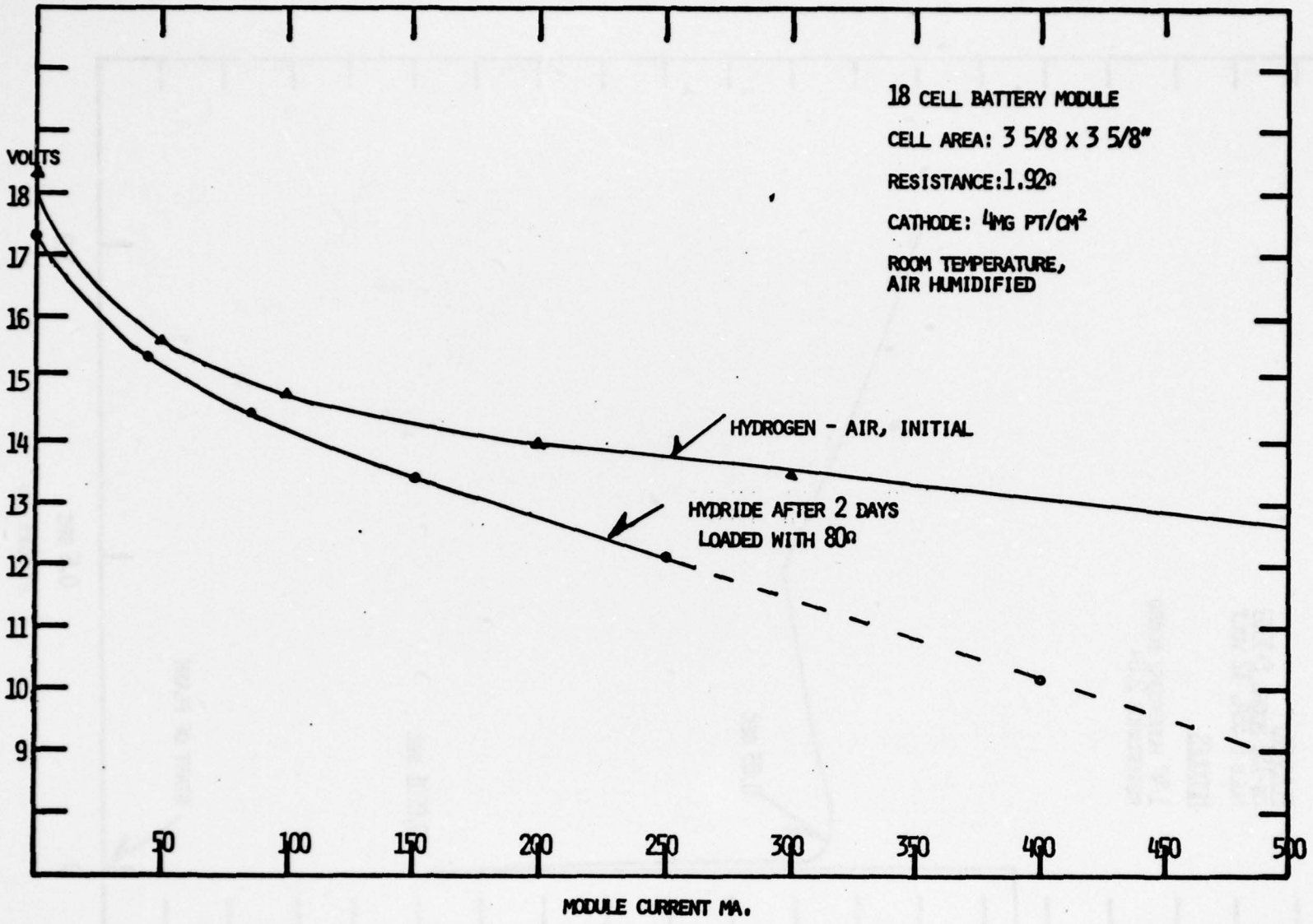


FIGURE 9

CURRENT - VOLTAGE CHARACTERISTIC OF BATTERY MODULE

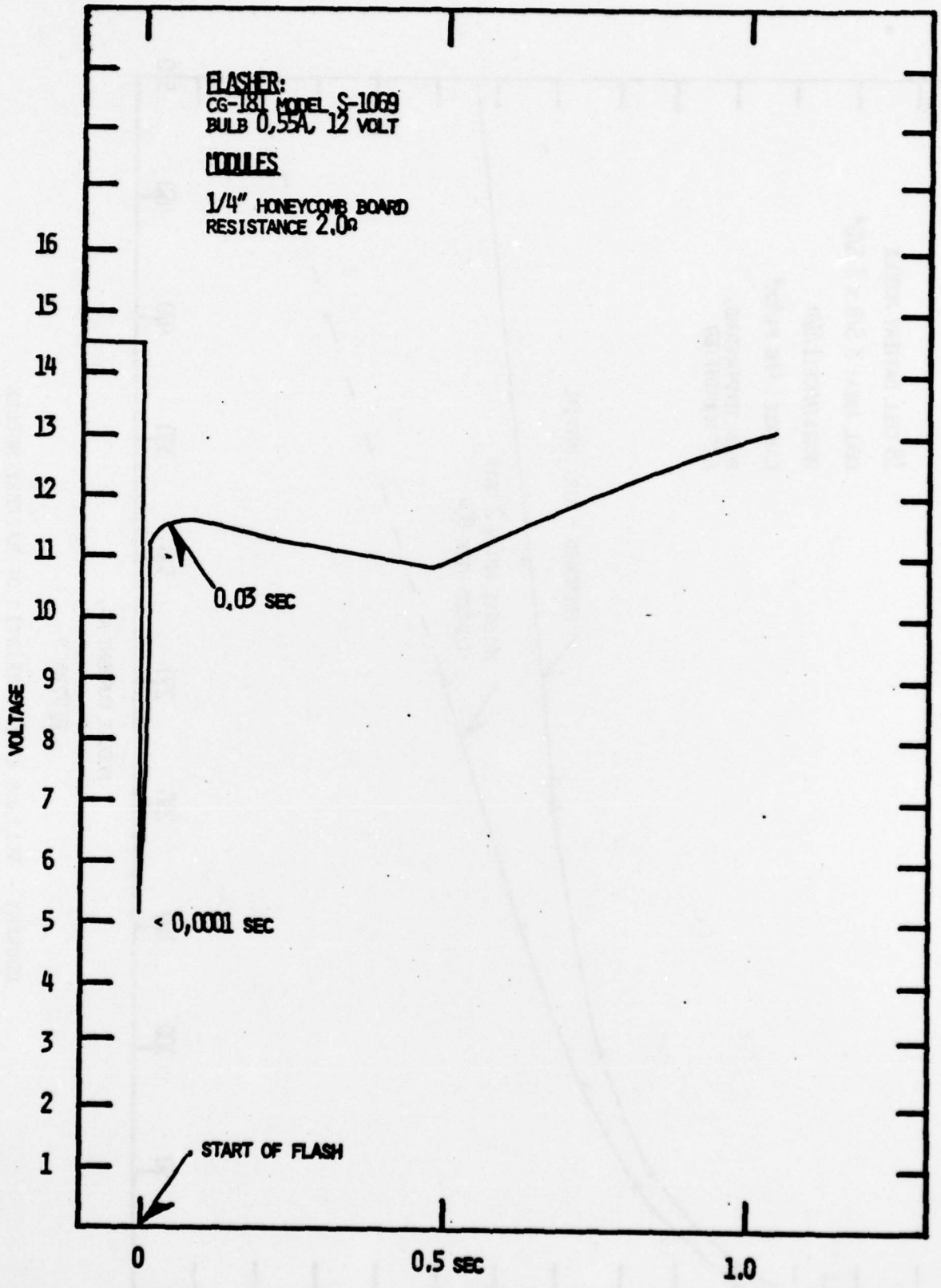


FIGURE 10

MODULE PERFORMANCE UNDER PULSED LOAD

With a capacitor, the voltage drop during flashing can be significantly reduced. For instance, a 300,000 MF capacitor (Sprague Powerlytic 36-DX-15 DC-7617L) used in conjunction with one module gives the following values. They represent the lowest voltage during flashing and the subsequent recovery peak.

2.03 A lamp	12-13.2 volts
1.15 A lamp	13-14 volts
0.55 A lamp	14.6-14.9 volts

7.2 Endurance Testing

Three life tests were carried out during the program. A nine-cell array was tested under constant load and up to three battery modules connected in parallel were evaluated under pulsed load.

7.2.1 Life Test of Nine-Cell Array (Constant Load)

The first multi-cell array constructed under the program was life tested to ascertain the suitability of the design. Performance was determined at an approximate current density of 2 mA/cm^2. Test data appear in Figure 11. The test fixture described in Figure 8 was used for the evaluation.

The hydride was placed directly in the metal container and located 8 inches from the cell board to simulate "worst case" conditions for water vapor diffusion. At a constant load of 38 ohms, the voltage declined from 6.33 volts initially to 5.78 volts after 1032 hours. About 70 percent of the hydride fuel was used up at this point. The weight gain indicates a current efficiency of 83.3 percent. The life test did not indicate major design deficiencies.

7.2.2 Single-Module Testing (Pulsed Load)

This section covers a life test with the first battery module fabricated under the program. The module is comprised of a polyethylene container and two nine-cell arrays and has an internal resistance (4.6 ohms) more than twice that of units fabricated later in the program. This is due to the use of Grafoil strips for current collection and intercell connection.

The module was charged with two 3-inch deep fuel boxes holding a total of nine pounds calcium hydride (-4 mesh) and tested under pulsed load with a 0.55A lamp (10 percent duty cycle). Intermediate power storage was not used.

Voltage during flashing varied between 10.5-10.8 volts except for an instantaneous initial decay to 3.8 volts. Between flashes voltage recovered to 14.3 volts. Performance remained about constant for 67 days. The test was discontinued because leakage developed on at least two cells. For failure analysis, see Section 7.2.4.

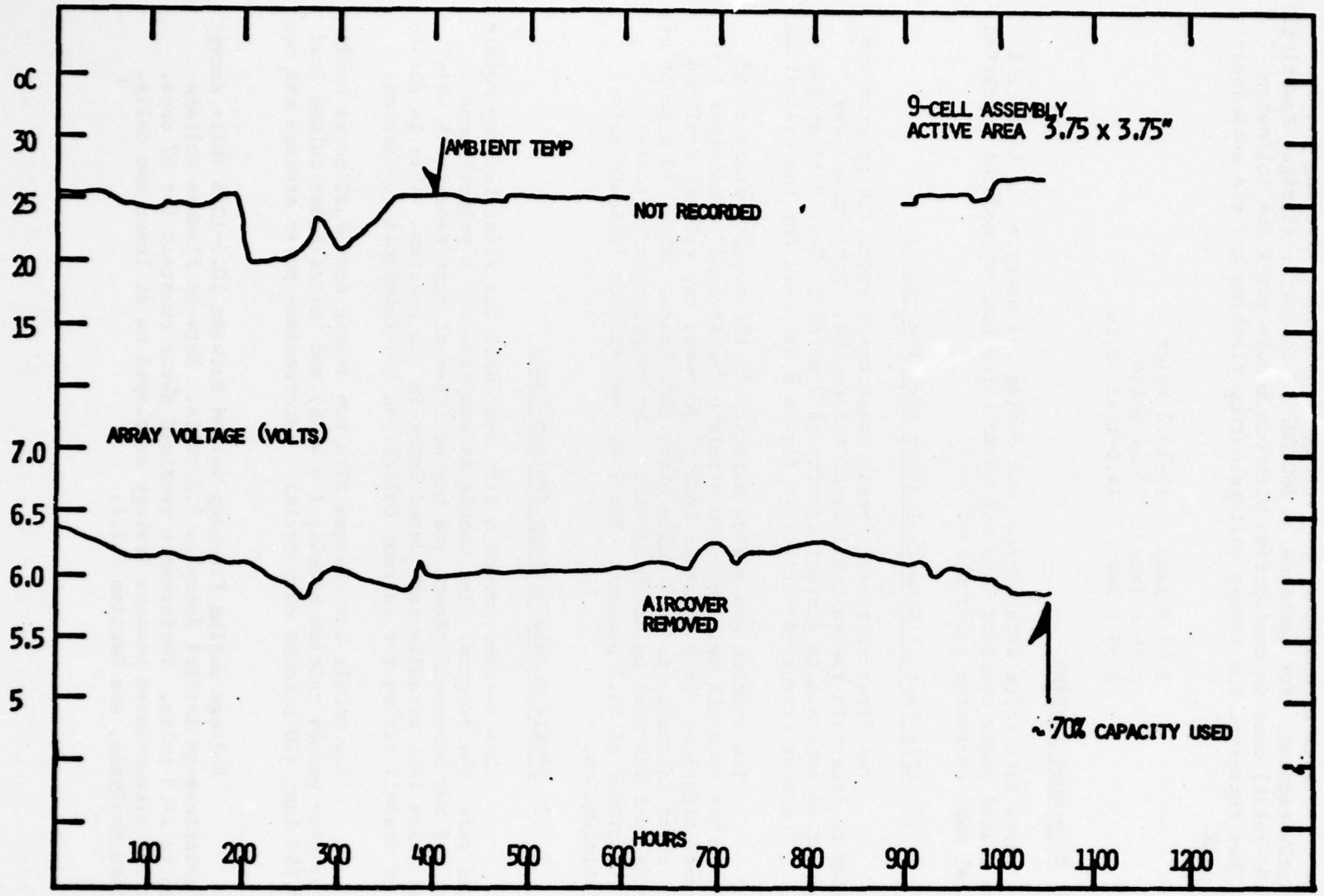


FIGURE 11

LIFE TEST OF NINE-CELL ARRAY WITH CALCIUM HYDRIDE FUEL
(Fuel Located 8 Inches From Cell Board)

7.2.3 Endurance Testing of Module Systems (Pulsed Load)

A life test extending with interruptions over a period of six months was performed with up to three battery modules connected in parallel.

The battery modules described in Section 6.0 were used in the evaluation and loaded with a solid-state flasher with a 1.15A lamp. Pertinent test data are summarized in Table 6 and Figures 12 and 13.

The test was initiated with two modules connected in parallel and a third module was added after 32 days. With three modules in excess of 12 volts could be maintained during flashing, using no intermediate power storage. After 64 days, the test was continued in an insulated box and the air humidified. The temperature increased about 5°C over ambient and 12 volts could be maintained during flashing.

The test was interrupted on the 87th day to check the status of the fuel container. One container was ruptured by the expansion of the hydride upon conversion to hydroxide.

Testing was stopped on the 115th day because of a severe performance decline which was traced to the neutralization of the electrolyte with ammonia released during the conversion of the hydride. This problem is discussed in some detail in the following section. Testing was resumed with rebuilt modules. They were refurbished with new cells and a cartridge placed between the fuel container and the cell array for the absorption of ammonia. The latter consists of corrugated boards with sulfonic acid resin. The resin is contained in the corrugations of the boards.

An additional change made on the modules involved increasing the number of air holes from one to five on each side of the module container. Its purpose was to improve air access and distribution for low temperature operation.

Testing of the prototype system was initiated at room temperature and after two days contained at 3°C in humidifed air.

Voltage at room temperature varied between 13.0-13.4 volts using 300,000 MF capacitor and decreased to 11.2-11.6 volts at the lower temperature.

7.2.4 Failure Analysis and Ammonia Absorption

Performance degradation observed in the life testing of battery modules discussed in 7.2.2 and 7.2.3 including the rupturing of the electrolyte matrix observed in some cells appears primarily related to the neutralization of the electrolyte with ammonia. Substantial concentrations of ammonium phosphate were found in the electrolyte leached from used cells and degraded modules showed a significantly higher resistance (3.3-3.6 ohms versus 1.85-2.0 ohms) due to the loss of acid.

TABLE 6

ENDURANCE TESTING OF BATTERY MODULES CONNECTED IN PARALLEL
(Load Flasher With 1.15A Bulb)

Battery module with fiberglass housing, active cell area 3-5/8 x 3-5/8", 18 cells per module.

NUMBER OF DAYS ON TEST	NUMBER OF MODULES ON TEST	TEMPERATURE	AIR HUMIDIFICATION	VOLTAGE DURING FLASHING	REMARKS
0 - 32	2	Ambient	None	10 - 11	Test interrupted after 32 days to change fuel container, load not equally shared.
32 - 64	3	Ambient	None	11>	See voltage-current curves in Figures 11 and 12.
64 - 87	3	28°C	Yes	10.4 - 12.2	Test performed in insulated box. Temperature increases about 5°C over ambient. Interrupted on 87th day to check fuel container. Container ruptured and replaced.
92	3	28.5°C	Yes	10.2 - 13.1	
101	3	30°C	Yes	11.2 - 13.1	
108	3	27°C	Yes	9.0 - 10.7	
115	3	28.5°C	Yes	8.7 - 10.5	Test stopped because of steep performance decline. Failure due to neutralization with ammonia. Modules rebuilt and equipped with absorbent.
117	3	--	Yes	13.13 - 4	300,000 M F capacitor, for intermediate power storage.
127	3	3°C	Yes	11.2 - 11.6	

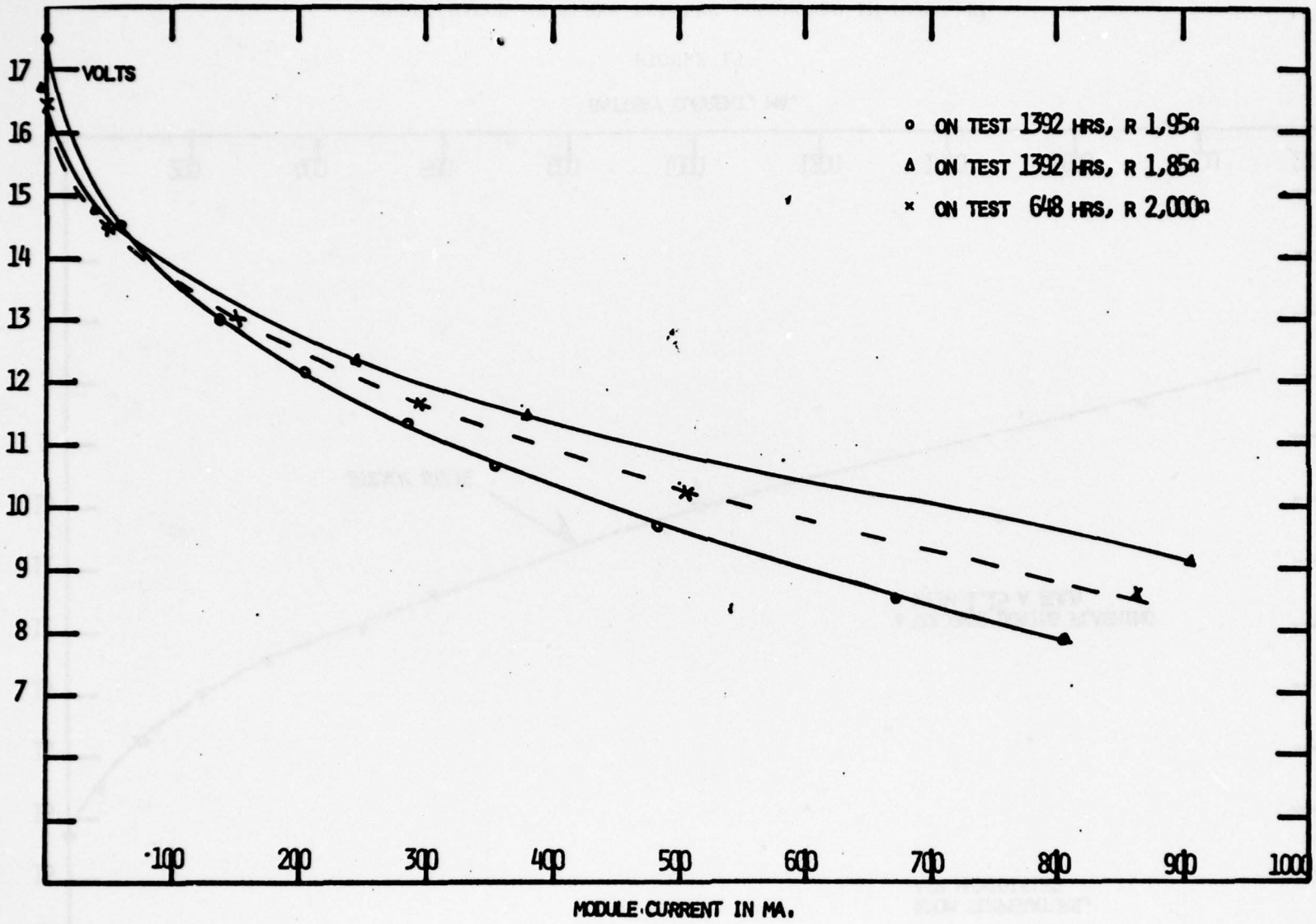


FIGURE 12

COMPARATIVE PERFORMANCE OF BATTERY MODULES WITH HYDROGEN
(Air Not Humidified, Room Temperature)

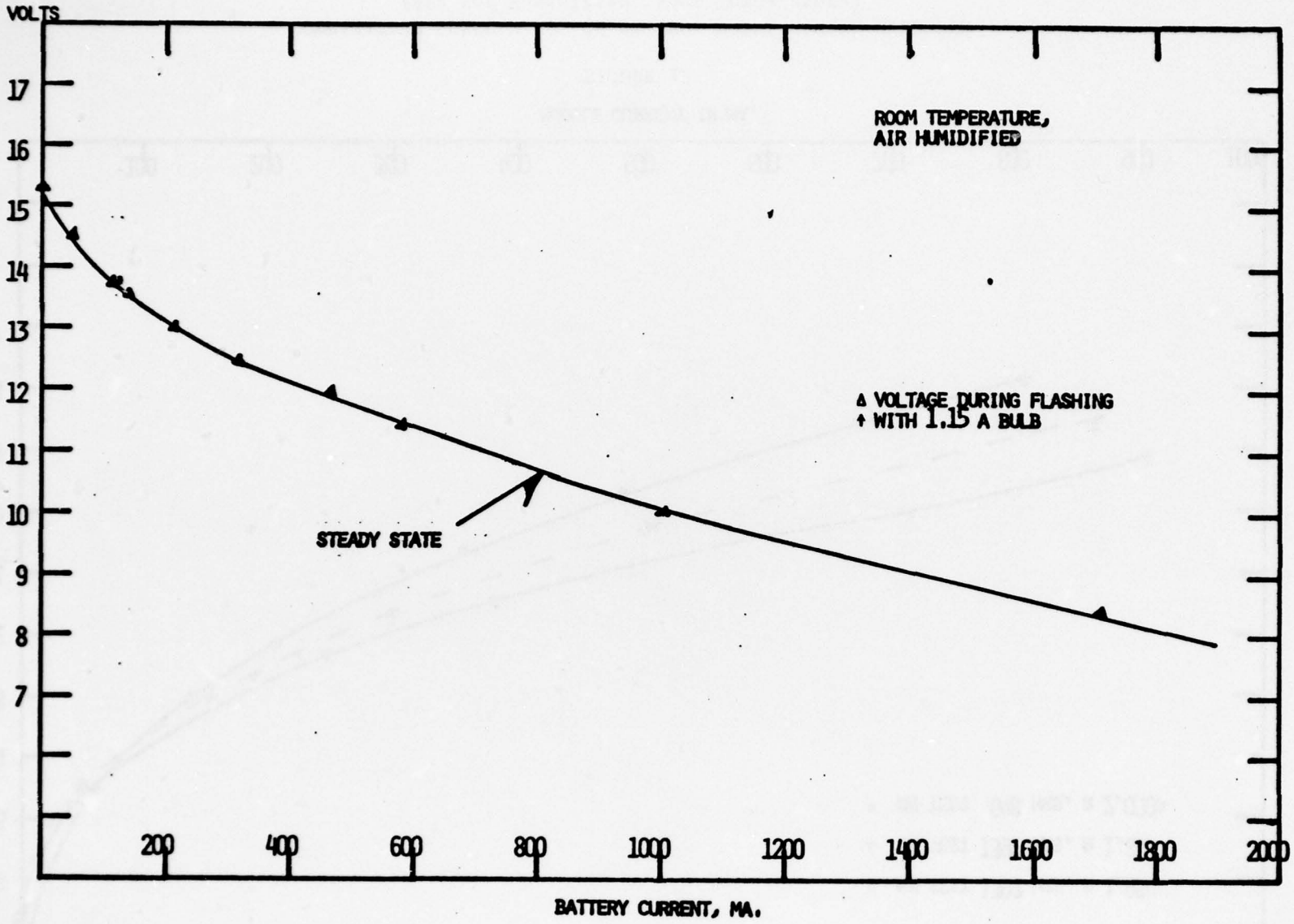


FIGURE 13

PERFORMANCE OF THREE MODULES CONNECTED IN PARALLEL
(Calcium Hydride)

Apparently, ammonia is formed in the conversion of hydride by reaction with water vapor from calcium nitride, an impurity present in commercial calcium hydride (nitrogen content 0.5-1.0 percent).

To proceed with the life testing discussed in 7.2.3 an attempt was made to remove ammonia by an absorbant placed between the cell array and the fuel container. An absorbent is required which does not interfere with the water transfer from the fuel cell to the hydride fuel. After prior testing with ammonia containing hydrogen mixtures Amberlyst 15, a sulfonic acid resin manufactured by Rohm & Haas was selected. Preliminary testing in battery modules indicated some interference with water transfer at low temperatures.

8.0 REVISED MODULE DESIGN

This section is concerned with a revision of certain design features of the battery module. The revision is based on evaluation results summarized in Section 7.0 and addresses questions concerning sealings of the module container and the cell array. The number of cells per cell array is increased from 9 to 10 to improve module voltage. Cell configuration is changed from square to rectangular to minimize deflection of the cell board. Modifications of the cell array are also considered to simplify fabrication and assembly of this component.

They include the use of a closed cell Neoprene foam rubber gasket, rather than Vaseline for sealing of individual cells, and a perforated foam rubber pad bonded to one cell board to assure uniform compression of cells while allowing for some deflection of the cell board.

The changes are conceptional and prior experimentation is required.

Referring to Figures 5 and 6, the modified cell array consists of the following major components:

1. Perforated cathode plate with 1/16-1/8 foam rubber padding

2. Perforated anode plate, same as above but without foam rubber

3. Ten cells, anode size 1-7/8 inches x 6-3/16 inches with 1/8 inch wide collection strips extending to the edge of the cell array. Intercell connection provided external to the board.

4. Neoprene foam rubber frame with openings to place spacer discs.

The design revision does not address the problem of ammonia absorption, possible modifications of the fuel container, or regulation of the air and moisture access to the battery module.

9.0 CONCLUSION

The program discussed in this report is a first step towards the development of hydride-based fuel cell batteries for use with aids to navigation.

The development effort carried out so far has confirmed the suitability of the hydride cell for the design of high energy density batteries. However, for the operation of aids to navigation certain deficiencies must be overcome. They are:

1. Low temperature performance must be improved
2. The fuel waste in high humidity environment is excessive
3. The neutralization of electrolyte with ammonia must be eliminated.

Considerable additional work is required to arrive at applicable hardware. Specific questions are discussed in some detail below.

Cell and Module Design

The cell and battery design outlined in Sections 6.0 and 8.0 is consistent with design goals (Table 6) with one important exception: no provision is made for adjustment of the air supply to the fuel cell to ascertain battery operation at low temperature and acceptable fuel utilization at elevated temperatures under humid conditions.

For automatic adjustment of the air supply to the required level, an air blower activated by a voltage signal may be required.

Pulsed-Load Performance

Battery operation under pulsed load without intermediate power storage is only possible in large capacity systems or by increasing the number of cells per battery module with a corresponding decline in fuel efficiency. If 18 cells are used per module, at least six modules will be required to maintain battery voltage above 13 volts with a 1.15 A bulb (10 percent duty cycle). In most uses intermediate power storage with a capacitor or a small storage battery appears preferable.

Fuel Containment

Containment of the hydride in a cardboard box with a paper honeycomb insert assures its location in close proximity to the cell array. The enclosure does not interfere with reactant and water transfer at the rates requires for battery operation. It does affect, however, battery start-up since air entrapped in the fuel box is only slowly released. A change in the mode of fuel containment may be desirable because of this consideration. The volume required for expansion of the hydride fuel upon conversion to hydroxide has not been conclusively determined with the testing performed so far.

Fuel Utilization

Fuel utilization appears largely dependent on the amount of moisture taken up by the cell from ambient air. Under moist conditions, excess hydrogen is formed which is not utilized for power generation. Fuel losses due to moisture take-up can be substantial and are best minimized by regulating the amount of air admitted to the cell. Reactant cross-diffusion does not appear to be a major source of fuel loss in an operating hydride cell. This may be related to the fact that, under steady-state conditions, hydrogen concentrations in the cell are low, possibly below 10 percent (balance nitrogen).

Calcium Hydride Fuel

Calcium hydride is a suitable fuel choice for hydride batteries because of its high reactivity towards water vapor and its comparatively low cost. The hydride contains between 0.5-1 percent nitrogen which is introduced as impurity of the calcium metal used in its manufacture. Upon reaction with water vapor, the nitride is converted to ammonia which in turn neutralizes the electrolyte and thus deactivates the cell.

Ammonia removal is possible by absorbents placed between the hydride and the cell array. This approach requires, however, further investigation.

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